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Abstract

This paper presents a concept for a human mission to Mars orbit that features direct robotic exploration of the planet's surface via teleoperation from orbit. This mission is a good example of Human Exploration using Real-time Robotic Operations (HERRO), an exploration strategy that refrains from sending humans to the surfaces of planets with large gravity wells. HERRO avoids the need for complex and expensive man-rated lander/ascent vehicles and surface systems. Additionally, the humans are close enough to the surface to effectively eliminate the two-way communication latency that constrains typical robotic space missions, thus allowing real-time command and control of surface operations and experiments by the crew. Through use of state-of-the-art telecommunications and robotics, HERRO provides the cognitive and decision-making advantages of having humans at the site of study for only a fraction of the cost of conventional human surface missions. It is very similar to how oceanographers and oil companies use telerobotic submersibles to work in inaccessible areas of the ocean, and represents a more expedient, near-term step prior to landing humans on Mars and other large planetary bodies. Results suggest that a single HERRO mission with six crew members could achieve the same exploratory and scientific return as three conventional crewed missions to the Mars surface.

Introduction

In a previous paper, we outlined a strategy for human exploration that combines elements of both human spaceflight and robotic exploration in a cost-effective strategy for exploration that could be adapted to multiple targets in the solar system (Refs. 1 and 2). This Human Exploration using Real-time Robotic Operations (HERRO) (Ref. 1) approach differs from the traditional view of human exploration, in that it does not land humans on planetary surfaces within large gravity wells. It instead envisions piloted spacecraft sent on missions that orbit, rather than land on, planetary targets. The crew then explores the surface via teleoperation of robotic vehicles deployed on the surface.

HERRO provides the cognitive and decision-making advantages of having humans at the site of study by allowing real-time command and control of operations and experiments. With the humans in a nearby vehicle, and hence engaging in teleoperation in nearly real-time operation, HERRO realizes most of the advantages of direct human engagement via a virtual human presence on the planet with substantially less flight hardware and risk (Ref. 3). The strategy is not intended to replace human presence on the surface, but rather offers an incremental pathway, developing the in-space transportation systems and many of the technologies needed for eventual human landings (Ref. 4).

This paper presents a conceptual design for a HERRO mission to Mars orbit. The general concept is shown in Figure 1, which illustrates the principal elements comprising the mission. The Crew Telerobotics Control Vehicle (CTCV) provides transportation for the six-person crew between Earth and Mars, and serves as the base of operations for the 1-1/2 yr stay in Mars orbit (Ref. 5). During this period, the crew operates three teams of telerobots positioned at different locations on the surface. Each telerobotic team consists of a "Truck" transporter and two "Rockhound" explorers. Each Truck serves as the communications node between the CTCV and its robotic team, and serves as the "mother ship" for the Rockhounds. The paper addresses the design of these elements, and also outlines the concept of operations for the mission.

HERRO-Mars Mission

The HERRO-Mars mission architecture is similar to NASA's Design Reference Architecture (DRA) 5.0, which was completed in 2008 to assist exploration planning efforts (Ref. 6). The DRA 5.0 reference focuses on crewed missions to the Mars surface, and actually envisions three separate missions launched over a period of 6 yr that explore three different regions on the surface. The area explored on each mission is limited to roughly a 50-km traverse from the landing site (100-km diameter area).

DRA 5.0 features split-sprint missions in which the cargo elements are sent out prior to the crew leaving Earth. For each mission, two cargo vehicles are first sent to Mars, each one assembled using two heavy-lift (130 mT heavy lift) launches to LEO. A Nuclear Thermal Rocket (NTR) propelled (Ref. 7) Mars Transit Vehicle (MTV) is assembled in low Earth orbit (LEO) over a series of three heavy-lift launches. A final launch of an Ares-I (or equivalent) human-launch vehicle delivers the crew capsule/service module with the six-person crew to the assembled MTV. The crew flies on a 180-day conjunction-class trajectory to Mars, and stays on the Martian surface for approximately 500 days in the predeployed cargo and habitat elements. Once surface operations

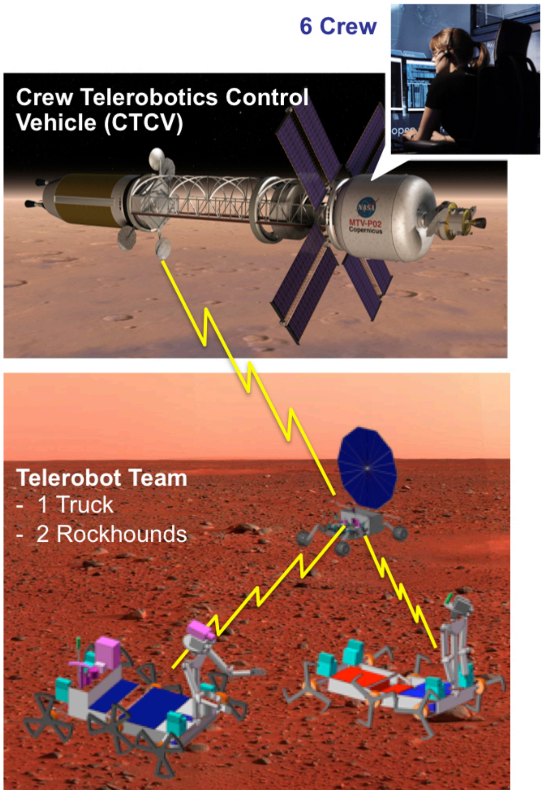

Figure 1.—HERRO-Mars mission elements.

are complete, the crew uses the ascent vehicle predeployed on the surface to return to the orbiting MTV, which then propels itself to a 180-day Earth return trajectory. The crew-return capsule returns directly to Earth, while the remaining MTV flies by. Each DRA 5.0 mission requires a total of seven heavy-lift (Ares-V or equivalent) launches, plus one launch of a six-person crew capsule/service module vehicle on a human-rated launch vehicle with the crew (Refs. 8 to 10).

HERRO-Mars Architecture

The goal of the HERRO-Mars mission is to achieve a level of scientific exploration comparable to that of DRA 5.0 in terms of number of sites explored and the quality of the science gleaned at each site. The architecture, which is shown in Figure 2, features a Crew Telerobotic Control Vehicle (CTCV) (Ref. 8), very similar to the MTV in DRA 5.0 (Ref. 6) Surface exploration elements include three “Truck” rovers (Ref. 9), each of which supports two teleoperated geologist robots, called “Rockhounds” (Ref. 10). Each of the three Truck/Rockhound groups is launched separately on an Atlas-V or Delta-IV, and is predeployed on Mars using an aeroshell-based lander system. Another element that could be included is a sample-return system to bring selected rock and regolith samples back to the CTCV, but such a capability was not considered in this study.

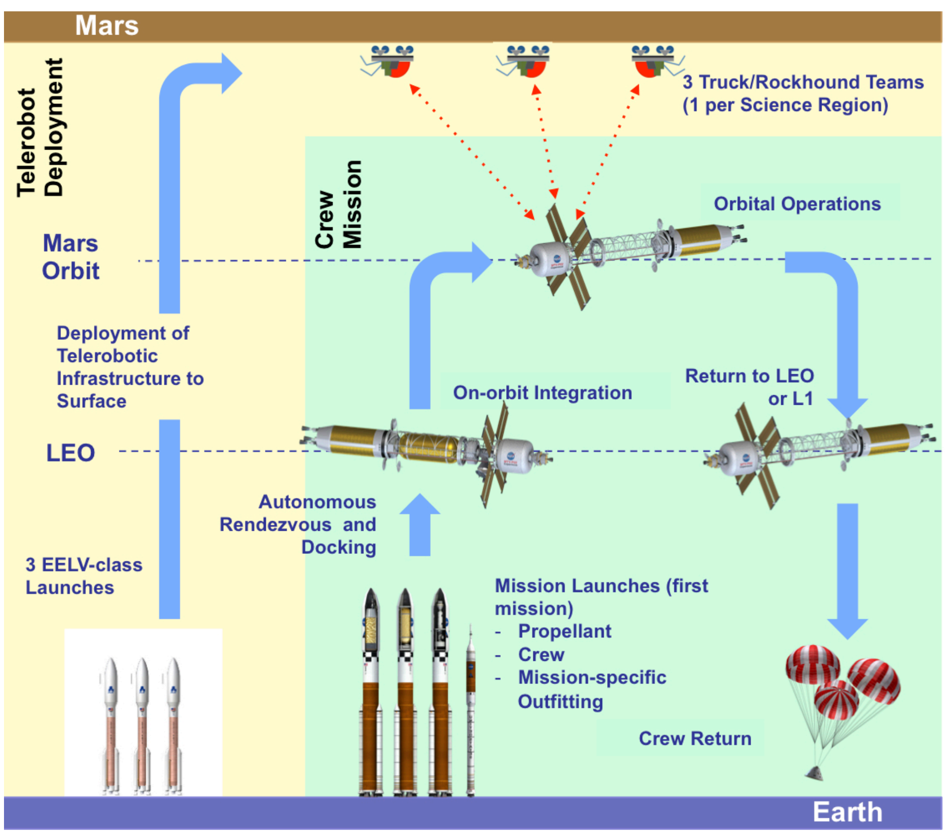

Figure 2.—HERRO-Mars mission architecture.

Each Truck/Rover group lands in a science location with the ability to traverse a 100-km diameter area. Each Truck carries the Rockhounds to multiple locations for science activities lasting up to several weeks. The truck is not only responsible for transporting the Rockhounds to these areas, but also for relaying telecontrol and high-resolution communications to/from the Rockhounds and powering/heating the Rockhounds during night and periods of inactivity. The Rockhounds effectively substitute as human geologists by providing an agile robotic platform with real-time control from the crew in the CTCV.

The HERRO-Mars mission begins 26 months before launch of the crew, with deployment of the three Truck/Rover groups. These groups land using proven entry, descent and landing techniques at three different locations around the planet. After these groups are checked out and operational, the CTCV, which requires three heavy-lift launches for assembly and one human crew launch for crew transport, departs Earth and follows the same conjunction-class trajectory to Mars as DRA 5.0. Once it inserts itself into a highly elliptical 12-hr Molniya-like Mars orbit, the CTCV beings to spin at 2.7 rpm to provide Mars g-level artificial gravity. After the astronauts have acclimatized, they begin to operate the Trucks and Rockhounds.

The mission duration entails nearly 500 days in Mars orbit. Once the surface exploration phase of the mission is finished, the CTVC despins and begins the return to Earth using an NTR burn. Final return of the crew is performed using the Orion vehicle on a hyperbolic trajectory. After the Orion vehicle has been jettisoned, the CTCV flies by Earth. Sufficient ΔV reserves are kept to return the CTCV to the Earth-Moon Lagrange point (L1), where it can be stored and refueled for future missions. A total of seven launches are needed to complete each mission.

HERRO-Mars Orbit

Communications between the CTCV and the ground science sites could be done either by a direct link or with one or more satellite relays. The relay option increases the flexibility of the choice of orbits, but has the disadvantage of greater complexity, added failure modes, and a larger number of elements. Thus, the study assumed a direct link, and an orbit that provides a direct view of the surface during telerobotic operations.

Lester and Thronson (Ref. 10) define the cognitive horizon for teleoperation in space, that is, "how distant can an operator be from a robot and not be significantly impacted by latency," in terms of the round-trip delay time. They note that this can be as low as 100 msec for full haptic (touch) control, and that at about 200 msec the delays become noticeable in visual feedback applications. They conclude that, "with sophisticated telepresence, there is little obvious value for humans to be closer to a target site than light can travel in ~100 msec: human perception and response is typically not much faster than this." This corresponds to a distance of 30,000 km, which represents the maximum altitude sufficient for highly effective teleoperation.

Studies of human factors have shown that astronaut fatigue results in poor performance as well as degraded judgment when work shifts exceed roughly 8 hr/day over extended periods. Thus, this study assumes no more than one 8-hr operation shift at each site per Sol (Mars day).

Additional considerations for orbit selection include:

- Minimize the required ΔV for orbital insertion and for trans-Earth injection;
  Allow selection of surface sites at multiple locations, including both high- and low-latitudes;
- Constrain telerobotic operations to occur during sunlight;
- Minimize ground-to-orbit distance primarily to reduce power required for high-bandwidth communications.

Although several orbits are possible within this set of considerations, the requirements for minimizing insertion ΔV and having teleoperation occur during surface daytime periods favored selection of the HERRO-Mars orbit shown in Figure 3. It has a 12-hr and 20 min period (i.e., 12 Mars hours, or exactly half a Sol), and is inclined 116° in a nearly-Sun-synchronous Molniya-type orbit (Ref. 6). The apoapsis on the sunlit side occurs twice per Sol, but the planet rotates under the orbit such that a site on the opposite side of the planet is seen with each orbit. Thus, two 8-hr shifts of scientist/teleoperators can explore sites on each side of Mars during each Sol.

Figure 4 shows the variation of elevation angle with respect to the local horizon for three widely dispersed telerobotic sites (Gale Crater, Mawrth Vallis, and the South Pole) over a one Sol period. It is assumed that the elevation angle must be at least 10° above the horizon for clear communications. In this

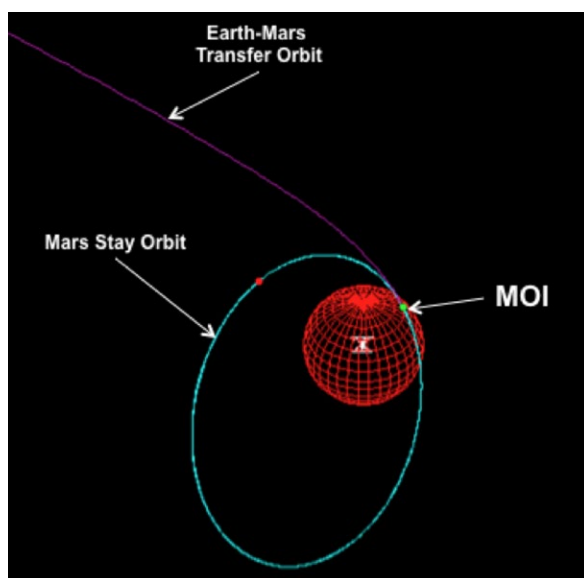

Figure 3.—HERRO-Mars 12-hr elliptical orbit.

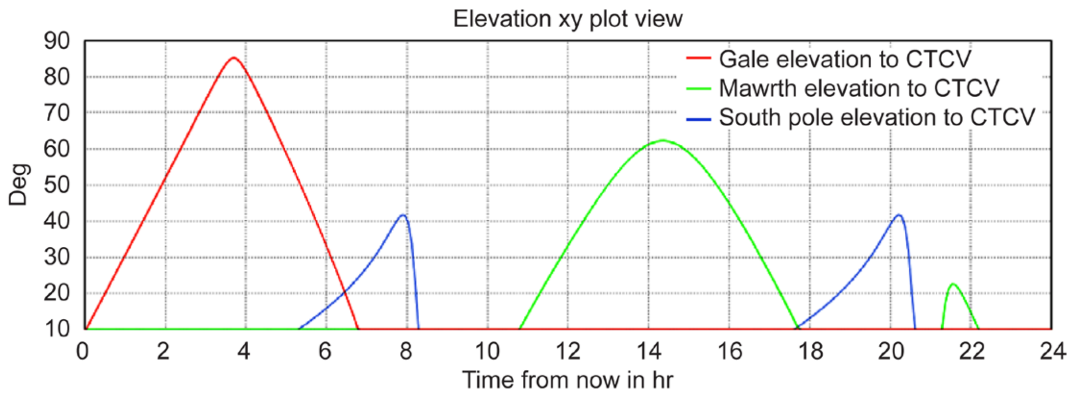

Figure 4.—Elevation angle with respect to local horizon at three sites over 24-hr period.

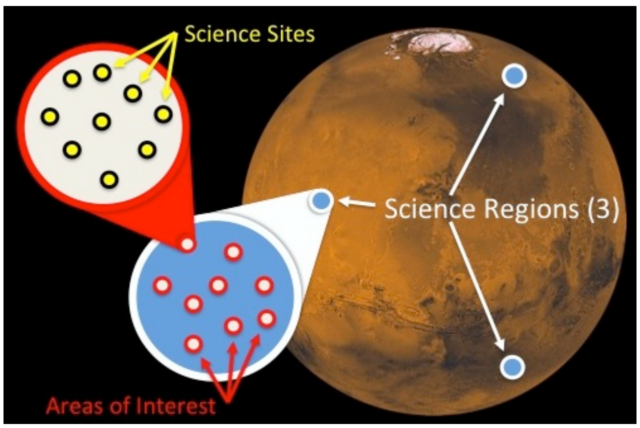

Figure 5.—HERRO-Mars exploration areas.

example, one shift operates at the Gale Crater site, while the second shift operates at the Mawrth Vallis site. Although the South Polar site is not utilized during this period, it is in full view for slightly over 2 hr at the end of both shifts. Thus, maintenance and minor science at that site could be performed if needed.

HERRO-Mars Surface Operations

Unlike the DRA 5.0 reference, HERRO allows the possibility of exploring multiple regions in the same mission. Each HERRO mission explores three widely-separated 100-km diameter science regions simultaneously.

Figure 5 shows how these regions are decomposed into areas of interest, which represent the endpoints for gross movement and transport of the Truck/Rockhound team in that region. The average separation distance between areas of interest is assumed to be 20 km, and each area is assumed to be approximately 1-km in diameter. In order to minimize time spent driving and to maximize time spent at each location, the 20-km journey should be accomplished in a single 8-hr shift. This requires that the Trucks be capable of a top speed of 1 m/s (3.6 km/hr).

Within each area of interest, there will be many individual science sites. These sites are the subject of detailed study with the Rockhound rovers, operated by geologists aboard the CTCV. Exploration of an area of interest will typically take place over a 2-wk period. In a given area of interest, the rovers will stop at numerous science sites, which have areas of roughly 10-m diameter, the territory covered typically in one Sol.

The baseline case is for the science operations to be done on two of the three regions during any given period; with the third region either dormant, or else in the "driving" phase of operations in which minimum time is spent by the geologist operator. This allows the mission to continue full-time operations even in the case of complete failure of the surface systems in one region, and reduced operations in the case of loss of two sets of telerobots. For the candidate landing sites chosen, the third landed operations region is located in the south polar region, and the orbit is phased to permit operations on science sites during the polar summer.

The Mars Science Laboratory (MSL) spacecraft candidate landing site candidates were used as the potential science regions for the Truck/Rockhound telerobotic teams. In addition, a site in the polar region was chosen to demonstrate the ability to operate over a wide variety of latitudes. The study considered simultaneous exploration of three sites with combinations of the following candidate sites:

- Mawrth Vallis: 22.3° N, 343.5° E
- Holden Crater: 26.4° S, 34.0° W
- Eberswalde Crater: 24° S, 33° W
- Gale Crater: 4.6° S, 137.2° E
- North or South Polar Site

Rockhounds

Each science site is explored by two Rockhound rovers in a manner similar to how a team of geologists would conduct field research on Earth. By emulating human geologists working together in the field, the Rockhounds allow cooperative action by both geologists. They are designed to

provide: agility, high definition video, and manipulation of samples (rock hammering and drilling). They must also be able to bring samples back for more complete x-ray and chemical analyses at the Truck or at the CTCV via a separately-deployed Mars ascent vehicle. Top speeds of 10 cm/s and climbing capabilities up to a 45° incline are baselined.

Figure 6 shows the final Rockhound design developed in the study. The most significant mobility feature is the use of “whegs” (a wheel-leg that combines the function of a leg with the operation of a wheel) to improve rough-terrain mobility (Ref. 12). This biologically-inspired locomotion system can achieve good traction on rough terrain (Ref. 13).

The Rockhounds are designed to handle short distance mobility on rough terrain, including rocky scree, heaps of stones and rocky debris. The six titanium whegs, along with an articulating body joint, enables the Rockhound to traverse terrain at least 0.5-m tall. The six whegs also enable operation, although degraded, in the event of a wheel failure. The body of the telerobot is articulated to allow the front section to lever upward to climb, while the four rear whegs provide stability and support. The Rockhound wheels are driven by individual motors, as well as the steering and body joints.

The body of the Rockhound contains batteries and avionics, with the batteries in the rear to help center the mass of the overall vehicle. The estimated average power is roughly 200 W for the 8-hr teleoperation events. Power comes from a 1,200 W-h set of rechargeable batteries (50 percent depth of charge) with a small solar array (~20 W) added to the top deck of the Rockhound for contingency power.

The aluminum-framed body is between 0.5- to 1.0-m long to promote stability. Navigation is provided by both LIDAR and navigational cameras located at each end of the vehicle. This allows steering control at both ends of the vehicle, and the ability to reverse out of tough locations. Thermal control is provided by foam insulation and small radiator panels, along with the option for radioisotope heater units (RHUs) for heating the motors and external instruments during nighttime storage.

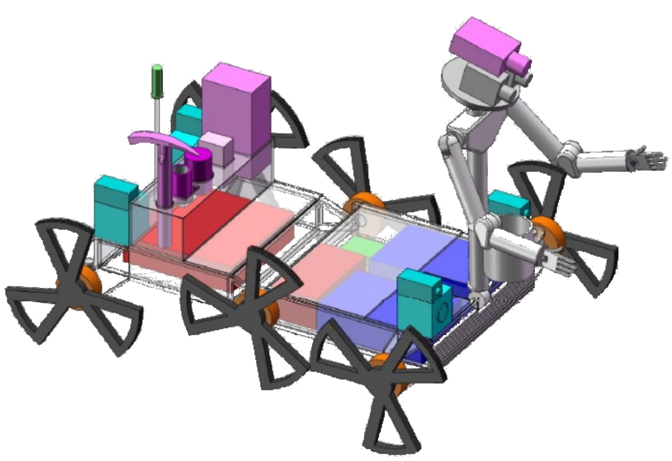

Figure 6.—Rockhound telerobotic explorer.

The science instruments aboard each Rockhound include a hyperspectral infrared (IR) camera, a Stereo HDTV camera and normal geologist’s tools for manipulating rock samples. These are operated by a teleoperated human equivalent robot, equivalent to the Robonaut unit developed at NASA (Ref. 14). The telerobot on the Rockhound uses highly sensitive hands for manipulating the samples directly, and is controlled in real-time by astronauts in orbit. The ability to replace the hands with the science instruments/tools protects the hands for their main duties of collecting samples. Samples are stored in separate containers in the rear of the Rockhound.

The telerobot torso is designed to lean over the surface to allow coordinated visual and hand operations. The visual science is provided by stereo high resolution cameras set in the “head” of the telerobot. All communications are provided by a 1/2 W radiated Wi-Fi type system with either a line-of-sight, 802.11 Wi-Fi antenna or a reflected 1-m whip antenna. These provide the 20 Mbps data rate at a maximum distance of 100-m with a healthy 30 db margin. The Rockhounds must be single fault tolerant and capable of operating for 18 months after landing 2 yr earlier. Delivering the Rockhounds early ensures that systems are operational before the crew leaves Earth. Environmental systems would need to address the possibility of dust storms and their impacts on the Rockhound performance.

Truck

The Truck, which is shown in Figure 7, plays the same role as the astronauts’ rover/habitat in the human landed mission. In addition to providing transport, laboratory and drilling functions, the Truck also functions as the charging station for the Rockhounds as well as a communications conduit with the CTCV. The Truck design uses a four-wheeled chassis with articulated control struts to raise and lower the vehicle with respect to the ground.

The truck design developed for this study can: charge up to 16 hr in sunlight; handle high bandwidth surface-to-orbit communications; drive for 11 days to 34 different sites over the 500-day period; carry a science laboratory payload; and can perform science operations when not driving (i.e., operate science laboratory, drill, winch and cable, and surface-penetrating radar).

The Truck is designed to achieve a top speed of ~1 m/s, with an average speed of 0.4 m/s and a range of several 100 km. It uses a standard four-wheel drive system, with each wheel independently operated by a separate motor. This gives the vehicle high ground clearance when needed to drive across rock-strewn plains, but allows the vehicle to lower down to the ground when the Rockhounds drive onto or off of the carrying platform. The articulation is also used to allow the vehicle to be folded up into the aeroshell for atmospheric entry. Finally, the vehicle body can be lowered to the ground to give a highly stable platform for operation of the drill to access the subsurface.

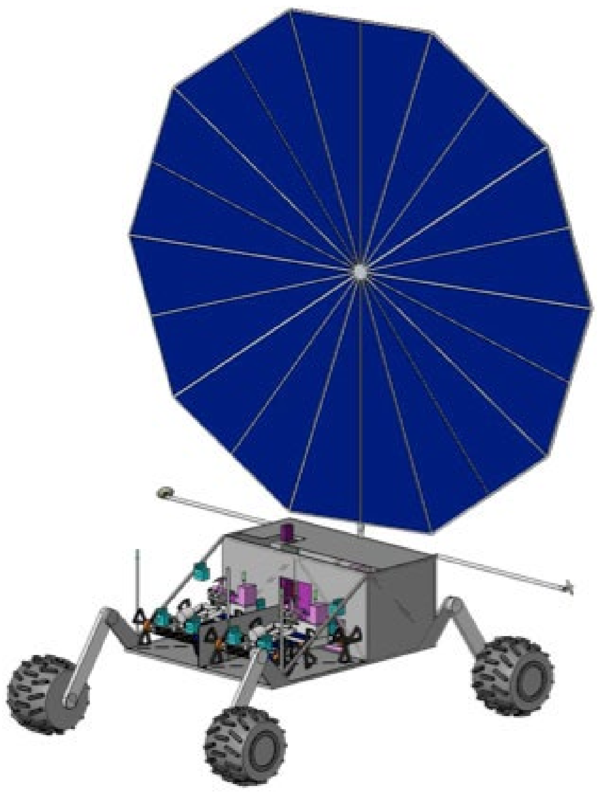

Figure 7.—Truck with its complement of two Rockhound Telerobots.

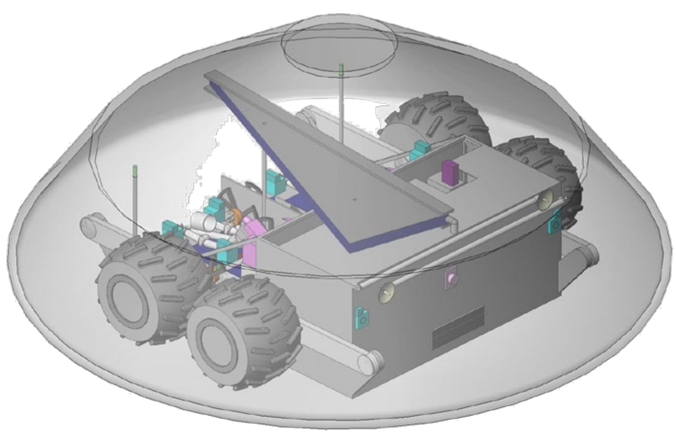

Figure 8.—Truck shown stowed inside the aeroshell for Mars entry and landing.

The truck mobility system is similar to that of the Nomad rover, tested in operations in both desert environments and in Antarctica (Ref. 15). The base of the Truck is roughly 2-m by 2-m, and the entire vehicle weighs slightly over 800 kg. A 4-m diameter pointable Ultraflex solar array and lithium-ion batteries provide power.

The Truck, with Rockhounds, is delivered to Mars using a larger cruise deck/aeroshell/sky crane based on the system that will be employed on the upcoming Mars Science Laboratory (MSL) mission in 2011. The vehicle is shown (with the Rockhounds) in Figure 7 in its stowed configuration inside the lander aeroshell. The total mass of 3,565 kg falls comfortably within the launch capability of an Atlas-V expendable launch vehicle for launch to the Mars-injection C_3 of 8.46 km^2/s^2.

HERRO-Mars CTCV

The CTCV provides the crew with an orbital habitat and platform to operate the Trucks and Rockhounds, as well as a means for transporting crew to and from Mars orbit. An important design requirement is to protect the crew from space radiation and the prolonged microgravity environment. To address these challenges, the design includes both water shielding for radiation and vehicle spinup/spindown to provide a centrifugal force to mitigate the effect of microgravity.

The design concept is shown in Figure 9. The vehicle is adapted from the MTV in DRA 5.0, which uses nuclear thermal propulsion and an inflatable TransHab-based crew habitat (Ref. 7).

The CTCV is divided into four elements. Each element is launched separately and integrated with other elements in LEO to form the assembled vehicle. These consist of the following, in order of launch from Earth:

- Habitat Element: Contains the crew quarters and all the components necessary to provide a safe haven for the crew.
- Drop Tank Element: Contains the hydrogen propellant to perform the first trans-Mars injection (TMI) burn. Once this maneuver is performed, the tank is dropped, leaving the saddle truss structure behind.
- In-Line Tank Element: Contains much of the propellant for the second TMI burn and Mars Orbit Capture (MOC) burn.
- Core Element: Contains the NTR engines and reactors along with the structure and tankage to carry the propellant for the trans-Earth injection (TEI) burn.

In addition to providing the high data rates needed for control and High Definition Television (HDTV) video from the rovers, the CTCV employs radiation shielding to ensure crew health. The radiation protection comes from water (14 tonnes) strategically surrounding only the sleeping and working areas of the vehicle where 2/3 of the crews' day is spent. This approach saves over 30 tonnes of water shielding that would be needed for the entire TransHab. Other radiation protection options include hydrogenated plastic materials, use of hydrogen propellant to protect the crew, and implementation of electromagnetic shields.

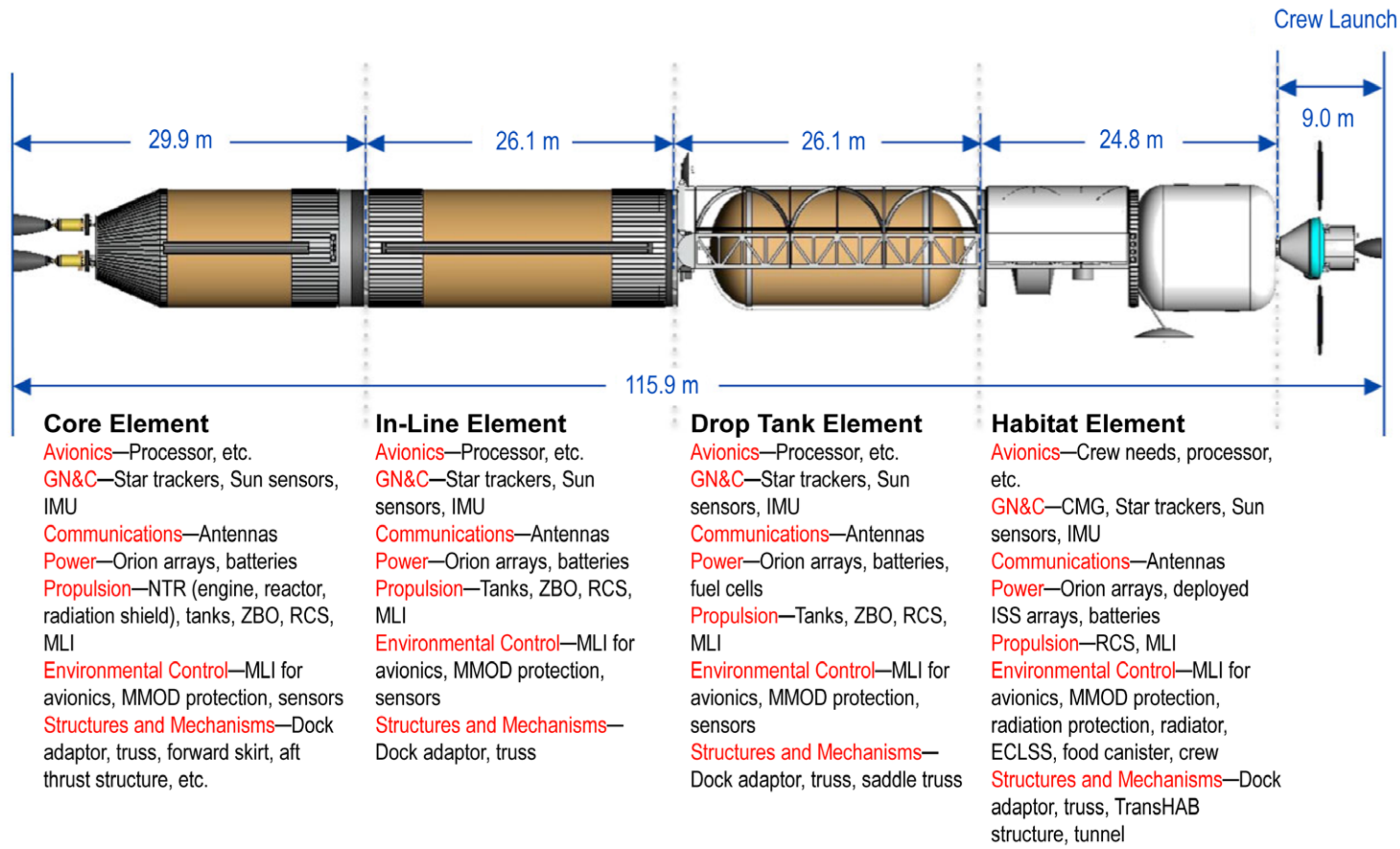

Figure 9.—Crew Telerobotics Control Vehicle (CTCV).

Crew health issues due to prolonged exposure to microgravity could be significant on a ~900-day mission. Therefore, artificial gravity was assumed for all mission phases, except during main engine firings. A Mars gravity level of 0.38 g, which is roughly midway between Earth and microgravity levels, was selected. It was assumed that this would be sufficient to maintain bone and muscle tone with the inclusion of a fitness regimen. The environment is created by spinning the CTCV at 2.7 rpm during the 500-day Mars stay. A higher level of effective gravity could be achieved with higher spin rates, but at the cost of larger Coriolis forces and other structural and dynamical complications. Other options that should be explored in future studies include small centrifuges and advanced exercise techniques.

Technology Challenges

There are several technologies that are important in enabling implementation of HERRO missions. The main one is the area of Life Support and Human Health. HERRO missions will place tremendous demands on the ability to sustain the crew over long multi-year missions, and will require the development of improved environmental control and life support systems to minimize the amount of water, oxygen and other life support fluids that have to be brought from Earth.

The PTV will also be exposed to large cumulative amounts of radiation stemming from cosmic rays and other sources. Countermeasures will have to be developed to mitigate these effects. For radiation, these include lightweight radiation shields and the use of multifunctional materials and structures. Examples include use of hydrogen propellant to shield astronaut crew quarters or construction of shields using stored water.

Another health concern is the deleterious effects of long-term exposure to microgravity. Work aboard the ISS over the last decade has improved our understanding of how to mitigate these effects. However, these countermeasures have been validated only to a year or so, and depend on individual physiology. For long multi-year missions, it is likely that methods of subjecting the crew to artificial gravity using a rotating structure and centrifugal acceleration will be necessary. This will require testing in a zero-g environment. It also places additional challenges on the overall spacecraft configuration and integration of its functions with the rest of the spacecraft.

A second major technology area is Robotic Systems. Most of NASA's work in this area has been aimed at highly autonomous systems and telerobots to support Shuttle, ISS and human operations in space. For HERRO, the emphasis will expand to include methods of providing high power, which will be necessary to effect faster mobility and real-time

operations. Candidates will include high-performance solar photovoltaics, advanced radioisotope generators and possibly fission power supplies.

Advanced sensors and improved mechanical dexterity will also be important. The reduced communications latency and possibility of employing high-bandwidth communications between orbiting crew and surface systems will push technology forward on telepresence and facilitate crew control.

HERRO missions do not require high thrust human-rated propulsion for landers and surface ascent. However, new in-space propulsion technologies could facilitate the implementation of HERRO missions by reducing propellant mass, trip times and overall costs. For modest capability missions (e.g., to the Moon and Lagrange Points), chemical propulsion will be adequate. Full capability missions (e.g., to more distant NEAs, and Mars and Venus orbit) could benefit through use of advanced technologies.

Nuclear thermal propulsion (NTP) is one technology that could double the propulsion performance for these missions. The U.S. had conducted an ambitious technology program in this area, called NERVA, over 40 yr ago. Several studies over the years have evaluated resumption of NTP development. Most of these have pointed to the need for new infrastructure and testing methodologies to reduce environmental impact, but there are no apparent showstoppers in moving forward with this work. There are also other forms of high performance propulsion, such as plasma propulsion, that could provide another route to faster and more cost effective missions to Mars, Venus and beyond. These include the Variable Specific Impulse Magnetoplasmadynamic Rocket (VASIMR) and high power electrodynamic thrusters.

Finally, HERRO missions will employ crewed EVA to the surfaces of NEAs, Phobos and Deimos. These will require the advancement of mobility systems that are safe and allow astronauts to make direct visits to these destinations. An example NASA technology that could play a role for this is the Manned Maneuvering Unit (MMU), which was demonstrated in use on the Shuttle prior to the Challenger accident in 1986. More advanced versions of the MMU would complement missions to small planetary bodies, along with new technologies for space suits and astronaut work performance.

The technologies discussed here are only a portion of the total number that would be suitable to HERRO-type missions. Other technologies, such as cryogenic fluid management, communications, advanced materials and structures will also be important.

The Case for Phobos

An alternate possibility as a target for the HERRO-Mars teleoperation is to place the teleoperations base on Mars' moon Phobos. This location has been proposed by others. One advantage is that Phobos is in itself a target of some scientific interest. It is a small body with a reflectance spectrum and presumed composition similar to a type-C asteroid, but in a close orbit around a planet. Since it has only a very low gravity, access to the surface is comparatively simple, without the difficult engineering challenge of a Mars lander/ascent vehicle. As a base for operation of science telerobots on the Martian surface, it has both advantages and disadvantages. The distance from the Martian surface, about 6,000 km, is low enough that teleoperation could be accomplished with negligible speed-of-light delay. The most significant advantage is that Phobos itself will provide shielding against cosmic radiation from half of the sky, and Mars, viewed from Phobos, will block radiation from 7 percent of the remaining sky. Locating the teleoperation base in a crater on Phobos, or partially burying it in regolith, would allow additional shielding. Thus, using Phobos as a base would improve the radiation protection for the astronauts during the portion of the mission when they are in orbit around Mars.

However, Phobos also has considerable disadvantages for a teleoperation base. Although Phobos is not as difficult to land on as the surface of Mars itself, the concept of landing a base on Phobos would increase the complexity of the mission. The equatorial orbit of Phobos means that without a relay satellite, sites to be explored would be restricted to only low latitude sites, although many sites of scientific interest are at high latitudes. The 459 min period of Phobos' orbit means that even an equatorial site on the surface would only be in direct line of sight for a period of slightly over 4 hr, which is a short duration for a teleoperation shift. Finally, and most importantly, the ΔV required for reaching (and leaving) Phobos orbit is larger than that for reaching the assumed highly elliptical Mars orbit in this study. This higher ΔV substantially raises the propellant use, and hence increases the mission cost.

For these reasons, Phobos was not selected as a base for teleoperation on Mars, although it, as well as Deimos, are attractive targets for future HERRO style missions as science targets in their own right.

Summary

This study has shown the HERRO approach to be a highly effective, science-oriented strategy for exploring the surface of Mars. A comparison between DRA 5.0 and HERRO-Mars is shown in Table I.

In terms of duration and surface area coverage, HERRO-Mars achieves approximately the same exploratory return as the entire DRA 5.0 campaign, which consists of three individual human-landed missions.

DRA 5.0 requires 27 separate launches, of which 21 are Ares V-class heavy lift vehicles. HERRO-Mars, on the other hand, requires 13 launches, of which only four are heavy lift. In fact, seven or almost half of the launches are performed with existing Atlas V or Delta IV-class vehicles.

TABLE I.—COMPARISON BETWEEN DRA 5.0 (SURFACE MISSION) AND HERRO MARS MISSIONS

Criterion	DRA 5.0 Campaign	HERRO
Science campaign: 3 × 100 km radius, widely separated regions	*Three separate manned landed missions*, landing in three locations, preposition cargo one opportunity early	*One manned orbiting mission*, telerobotically exploring three locations, preposition telerobots one opportunity early
Location/duration	Three 500 day stays, each at a 100 km radius region	Three 100 km radius regions, simultaneous telerobotic exploration
Launches (entire campaign)	*21 Ares V + six Ares I*	*Four Ares V, two Ares I, seven EELVs* Four heavy lift + two Ares I + three rovers = three EELVs + three sample return to LMO = three EELVs + one sample rendezvous (LMO to manned vehicle)
Vehicle elements (entire campaign)	Three Mars transfer vehicles, six Orion, three cargo lander, three cargo habitat; three hab lander, three ascent vehicle, three habitat, six pressurized manned rovers, six unpressurized manned rovers (27 NTR engines)	One Mars transfer vehicle, three telerobot truck carriers, six telerobot Rockhounds, three sample ascent systems one sample rendezvous system (three NTR engines)
Crew (entire campaign)	18, three crews of six	Six, four geologist teleoperators (two shifts), two support
Technology development	Long duration crew on-orbit habitat, cryofluid management and propellant transfer, nuclear thermal rockets, radiation protection, aerocapture (cargo) landing descent, landing ascent systems, Mars unique habitats/ manned systems, manned rovers, surface suits, surface reactor, in-situ propellant production for ascent system	Long duration crew on-orbit habitat, cryofluid management and propellant transfer, nuclear thermal rockets, radiation protection, artificial gravity, telerobotics, teleoperated rovers, sample ascent system, teleoperated sample rendezvous system

The approaches also differ dramatically in the number of individual spacecraft and spaceflight elements required for the mission. DRA 5.0, which consists primarily of man-rated hardware, involves use of three MTVs, six Orion capsule/service modules, and three cargo landers, cargo habitats, habitat landers, ascent vehicles and habitats. Three pairs of pressurized rovers and unpressurized rovers are also required, in addition to 27 NTR engines.

HERRO-Mars requires only one CTCV (three NTR engines) and three Truck/Rockhound teams (i.e., three Trucks, six Rockhounds). Inclusion of sample-return capability would also require three sample-ascent systems and one system for orbital rendezvous and collection by the CTCV.

HERRO-Mars requires many of the same technologies needed for DRA 5.0. The main difference will be in crew health and habitation, which HERRO-Mars will entail longer duration exposure to microgravity and cosmic rays. However, it appears that a combination of new technology plus innovative design solutions (e.g., spinning CTCV to produce artificial gravity, water radiation protection) could readily address these issues.

Conclusions

A concept for a human mission to the orbit of Mars has been presented. The concept features the use surface exploration via telerobotics operated by the crew in orbit. Although no cost estimates were derived for this mission concept, it is readily apparent that it could be implemented with substantially less infrastructure than a human Mars surface mission.

There are several advantages in considering telerobotic surface exploration for human spaceflight. First, it expands the spectrum of missions by opening up a new world for intensive, robot-facilitated human exploration. In addition it offers a synergistic human/robotic approach to the study of scientifically rich planets by eliminating speed-of-light delay, increasing effective data and command rates over autonomous robotic missions.

Future work will focus on more refined designs for the CTCV and the telerobotic surface elements. It would also be desirable to develop cost estimates for these mission concepts and compare them with those for more conventional exploration missions.

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14. ABSTRACT
This paper presents a concept for a human mission to Mars orbit that features direct robotic exploration of the planet's surface via teleoperation from orbit. This mission is a good example of Human Exploration using Real-time Robotic Operations (HERRO), an exploration strategy that refrains from sending humans to the surfaces of planets with large gravity wells. HERRO avoids the need for complex and expensive man-rated lander/ascent vehicles and surface systems. Additionally, the humans are close enough to the surface to effectively eliminate the two-way communication latency that constrains typical robotic space missions, thus allowing real-time command and control of surface operations and experiments by the crew. Through use of state-of-the-art telecommunications and robotics, HERRO provides the cognitive and decision-making advantages of having humans at the site of study for only a fraction of the cost of conventional human surface missions. It is very similar to how oceanographers and oil companies use telerobotic submersibles to work in inaccessible areas of the ocean, and represents a more expedient, near-term step prior to landing humans on Mars and other large planetary bodies. Results suggest that a single HERRO mission with six crew members could achieve the same exploratory and scientific return as three conventional crewed missions to the Mars surface.

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